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Whither Refining?

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WHITHER REFINING?

by

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ABSTRACT

This paper is a survey of both journal and patent literature over approximately the last 20 years in selected areas of refining. Hopefully, this will provide a perspective of where refining has been going during this time period. A little speculation about the future direction of refining and the challenges it may face is also included.

INTRODUCTION

This paper is a survey of both journal and patent literature over approximately the last 20 years in slelected areas of refining. Refining or beating (terms used interchangeably) is defined as the changes in fiber structure that are necessary to maximize the papermaking potential of a pulp. Hopefully this will provide a perspective of where refining has been going during this time period, and will speculate a little about the future direction of refining and the challenges it may face.

One's perspective is obviously tied to one's experience in the field. Mine began about 30 years ago under the direction of Bertil Ivarsson at Westvaco Corporation. Despite being very green about refining and papermaking in general, I soon realized that paper physics was an essential discipline needed to understand the changes in fiber structure and their impact on paper machine runnability and paper properties.

Refining has many facets and points of view, including stock preparation and paper mill personnel, refiner manufacturers, plate suppliers, and those in research institutions and academia. My perspective is from the latter category. Furthermore, my main concern, which is central to refining, is with refining action and the changes it produces in water removal and paper properties. Different terminologies are often used for refining action, e.g., in production, the terms wet beating, brushing, bruising, and cutting are familiar, whereas fibrillation, curl, microcompressions, etc., are the currency of the researcher.

LITERATURE SURVEY

The literature on refining is quite extensive (1); however, there have been several notable reviews (2)-(7) during the last 20 years. Furthermore, refining has been the subject of a number of conferences organized by the Institute of Paper Science and Technology (formely The Institute of Paper Chemistry) and PIRA (Paper Industry Research Association) International, Leatherhead, UK (8)-(11).

The general relationship between raw materials, refining, papermaking, and the properties one are trying to produce is shown in the diagram below. We note that both refining and papermaking involve wet state variables, while paper properties are mainly in the dry state.

	← wet state	→	← dry state →
RAW MATERIALS ⇒	**REFINING ⇒**	**PAPERMAKING⇒**	**PAPER PROPERTIES**
virgin, recycled fibers	changes in fiber structure	water removal	surface & bulk
nonwood fibers			
genetically modified fibers			

According to the review by Page (4), there are nine types of fiber structural changes as given below:

<u>**Fiber Structural Changes Produced by Refining**</u>

1. **Cutting or shortening of the fiber**

2. **Fines production**

3. **External changes in fiber structure**

4. **Internal changes in fiber structure**

5. **Curling the fiber or curl removal**

6. **Inducing microcompressions or removing them**

7. **Dissolving or leaching out colloidal material**

8. **Redistribution of hemicellulose from the interior to the exterior of the cell wall**

9. **Surface abrasion at the molecular level to produce a more gelatinous surface**

The above changes in fiber structure are mainly produced by mechanical stresses imparted to the fiber by some type or combination of refiners. The extent to which changes are brought about will depend on a number of factors, i.e., type of fiber, pulp consistency, pH, presence of counterions, temperature, etc.

The treatment that a fiber needs will depend on the desired end-use performance of the paper being made. In other words, there is no one desirable treatment to fit all papermaking and paper property requirements.

In a production refining situation, once the desirable changes in pulp properties have been identified, the aim is to produce them with the minimum amount of fluctuation, even though the characteristics of the incoming pulp may be varying. Minimizing energy consumption and downtime (say due to plate wear) is also highly desirable. Changing refining action so as to alter the relative balance of the above nine refining effects is not an easy matter. Currently, the disk refiner is the most commonly used production refiner. In addition to the factors mentioned previously, plate design, energy input, and sizing of the refining system are the main factors controlling refining action.

Significant reviews of the refining literature were carried out by Attack in 1977 (2), Ebling in 1980 (3), Page in 1989 (4), and Hietanen and Ebling in 1990 (5). Attack stated that during the period of his review (20 years) refining of chemical pulps was reasonably well understood, but there was still a need to better understand the refining of high-yield pulps. Ebling and later Hietanen and Ebling carried out an extensive review of the refining literature. They concluded, and this may be an oversimplification, that one of the central problems of refining to be addressed is the breakdown of flocs entering the refining zone so that fibers can be more readily treated.

Page's review (4) concludes with seven goals for future beating research, which are summarized below.

Page's Goals for Future Beating Research

1. **More precise physicochemical description of the structure of the cell wall matrix.**

2. **Rapid measurement of fiber length, coarseness, cell wall thickness, and fibril angle.**

3. **Better characterization of raw materials and pulps.**

4. **Rapid measurement of beating effects, i.e., fibrillation, cell wall cracks, microcompressions, kinks, and curl.**

5. **Multivariate analysis of beating.**

6. **Improved images of beating zone, especially to capture individual fiber movement.**

7. **Mechanistic theory of beating action in terms of the stresses the fibers experience and their responses to those stresses.**

During the past seven years progress has been made toward addressing these goals, particularly items (2) fiber length, (4) kinks and curl, (5). multivariate analysis, and (7). mechanistic beating theory. Aspects of (5) and (7) are briefly discussed below.

5. Multivariate Analysis MVA

Factor analysis has been used by Howard, Poole, and Page (12) to examine published data involving a variety of laboratory beating processes, i.e., Aylesford Beater, Banning-Seybold Beater, PFI Mill, Lampen Ball Mill, Valley Beater, and a Noble & Wood Beater involving nine different pulps and the measurement of nine pulp and paper variables.

The data set was used by the above authors to determine the number of FACTORS or independent variables involved. The factors are mathematically derived, and through logical reasoning, their underlying meanings can be deduced. It was found in using the data for all pulps that three factors accounted for 94% of the total variance. The three factors were identified from the dependent variables involved to be ***(1). bonding, (2). fiber length and fines, and (3). microcompressions.*** For example Factor 1, accounting for 49.6% of the common variance, had a strong positive correlation with burst, breaking length, fold, and a strong negative correlation with scattering coefficient; hence, ***bonding*** was identified as the most likely candidate for Factor 1. It should be emphasized that none of these variables (or related variables) were measured, nor part of the original data set on which the MVA analysis was performed. Furthermore, it is not known to what extent bonding may be related to fundamental factors such as internal fibrillation, or external fibrillation.

The authors in their discussion recommend that an experiment be designed which would include a much wider range of treatments and measured variables. Once factors have been identified, variables termed "marker variables," e.g., fiber strength, fiber saturation point, fines content, fiber length, and curl index, would be measured.

Although the above factor identification seems reasonable, there could be alternative interpretations. Perhaps what is impressive is that just three factors were identified out of a possible total of nine, although Factor 2 did involve both fiber length and fines. Interestingly, the beating effects identified in Page's review (4) total nine.

7. Mechanistic Beating Theory

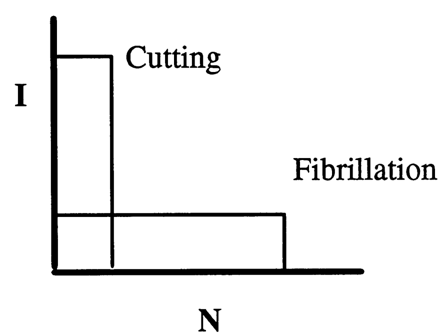
The more recent research of Martinez (7) and Kerekes and co-workers (13)(14)(19)-(22) has attempted in a systematic way, to address, in part, Page's 7th recommendation. Central to this work is the C-Factor concept in which the specific energy of refining **E** is decomposed into the number of impacts a fiber receives in the refining zone **N** and the intensity of those impacts **I.**

$$\mathbf{E} = \mathbf{N} \times \mathbf{I}$$

and if **P** is the net power input, **F** is the fiber mass flow, then ***C (or C-Factor) is defined as the capacity of the refiner to inflict impacts,*** and we have:

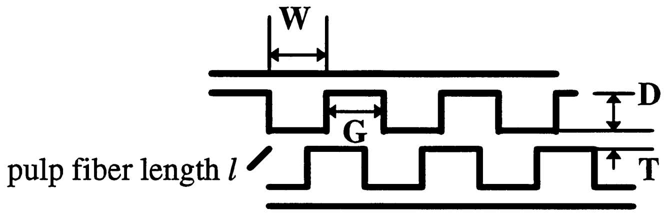
$$\mathbf{N} = \mathbf{C/F} \text{ and } \mathbf{I} = \mathbf{P/C}$$

I refers to some form of cyclic deformation imposed on the fiber by bar crossings.



We see from the above diagram (as given by Kerekes) that the same amount of energy can be imparted to the fibers in many different ways. At one extreme, we have a small number of impacts at high intensity which leads to cutting, and at the other extreme, a large number of impacts of high intensity, which lead to fibrillation.

Kerekes (13) has attempted to rigorously derive C-Factor, and the key issue is associated with the number of impacts a fiber is likely to receive as it passes through the refiner.



Now N^* is the number of impacts a fiber receives, and M is the mass of the fiber, and the rate of impacts is dN^*/dt and is proportional to the product $n_1 x\ n_2\ x\ \omega$ where n_1, n_2, and ω are, respectively, the number of bars on the rotor, stator, and the angular velocity of the rotor with respect to the stator. The correct estimate of the **proportionality factor** is, according to Kerekes, a crucial assumption of the analysis, and is estimated according to the probability of fiber contact with the leading edge of the bar, which is given by $l/(l + D + T)$.

Several cases involving fiber length and bar geometry were considered by Kerekes. Now the number of impacts per unit time on a fiber is given by:

$$dN^*/dt = [l/(l + D + T)] \times [l/2\pi r] \times [n_1 n_2 \omega]$$

Case 1: $(D + T) << l$, i.e., bar depth and clearance are small compared with fiber length.

Case 2: $(D + T) << l$ and $l = (W + G)$, i.e., only one impact at a time on a fiber from the bar of the opposing plate - $dN^*/dt = n_2\omega]$.

Case 3: $(D + T) >> l$, i.e., bar depth and clearance large compared with fiber length - $dN^*/dt = l^2 n_1 n_2\, \omega/2\pi r\ (D + T)$.

C-Factor analysis is perhaps the most rigorous and comprehensive theory developed to date, and in essence, builds on the theories or models of Brecht (15), Danforth (16), Rihs (17), and Lumianen (18). It has been applied to a variety of refiner geometries including the disk, conical, and PFI mill.

The C-factor is ultimately a function of plate geometry (bar width, depth, length, angle, and edge geometry), speed, consistency, fiber length, and coarseness for which equations have been derived (13), (14).

The structure of the fiber is modified by a fatigue process, i.e., the average number of impacts the fiber receives in the refiner N, with a certain level of intensity I as already stated. Cutting and fibrillation are treatments identified at the extremes of the treatment envelope. What other effects, as discussed earlier, are present, and what happens between these extremes have yet to be identified.

Refining action is concerned with how to efficiently and effectively impart changes to the fiber to improve its papermaking and product quality characteristics. If for the moment we limit our discussion to bar-type refiners, e.g., disk, conical, a variety of mechanical stresses are applied to the fiber either directly or indirectly. These stresses include shear, compressive, tensile, friction, and ploughing (7). By direct we mean the individual fibers would be receiving one or more of these stresses, whereas indirect would mean that the floc would be subjected to one or more of these stresses. It is also possible that fibers may be specifically oriented, as in a network to receive fiber treatment.

It is perhaps surprising when we consider the size of the softwood fiber, 2 to 3 mm length, 50 μm in width, that the moving elements of most refiners or beaters are large by comparison, i.e., 10 to 20 mm bar width. However, disk refiners do not, in general, act on individual fibers, but rather on fiber flocs, which are very prevalent in the consistency range associated with refining, i.e., 3 to 7%. It is through these flocs, which are subjected to the above stresses, that the individual fibers receive their treatment. Kerekes's group is also involved in the prediction and measurement of stresses that are applied to fiber flocs (19)-(22).

Steenberg's refining concepts involving grinding and ore milling (23)-(25) also appear to be relevant to disk refining. In Figure 1,we see how the gap or clearance in a refiner varies with the time the material is being treated. In the control situation A, the gap will decrease with time; however, if either long fiber B or fines C are added, the gap will respectively increase or decrease accordingly. In case C, presumably the decrease in gap would be equivalent to some point on curve A at the same total equivalent fines content. In case D, polyethylene oxide is added, which dramatically decreases the gap. This behavior might be interpreted as a change in the rheology of the stock, i.e., its effective viscosity, and/or as Steenberg argues, be related to the condition of the stock, i.e., does it ooze or consolidate as shown in Figure 1. In an oozing flow regime, it would be difficult to refine the fibers, while in the consolidation flow regime, the flocked fibers would be treated at a consistency higher than that going into the refiner. Interestingly, Steenberg (25) shows that a roughened surface, e.g., grooves, is necessary to promote the consolidation phase.

Experimental Refiners

Disk refining, the main means of fiber treatment in the paper industry, is a complex process. Whether there will be a paradigm shift to a completely different method of refining remains to be seen. In the meantime, there has been a significant effort to improve the disk refiner, at least as is indicated by the patent literature. How much control in terms of refining action and concomitantly changes in fiber structure we can ultimately exercise remains to be determined.

A number of novel attempts have been made to refine fibers, some of which have been designed to produce a specific refining action or change in fiber structure. These, as we shall see, include viscometric-rheological-type devices, ultrasonic methods, abrasive, and porous devices. Specialized production equipment has also been developed to produce more specific changes in fiber structure, including high consistency devices such as the Chemifiner (26) and Frotapulper (27) to produce kinked , curled, and microcompressed fibers. At the other extreme, homogenizers (28) have been used to produce microfirillated cellulose (essentially a breakdown of the fiber into its constituent fibrils).

A selection of these devices is shown in Figures 2, 3, 4, 6, 7, 8. The "Shear Refiner" (29) shown in Figure 2 was designed to measure the rheology associated with refining in a shear field, the energy consumed, and the treatment of enough pulp to make handsheets and evaluate the refining action. One critical question was whether turbulent flow was necessary for effective refining. As Figure 2 illustrates, the flow in the annulus of the shear refiner was laminar; furthermore, the energy consumption was considerably greater than a disk refiner at the same level of slowness. In retrospect, one reason for this might be due to the use of a fixed gap, i.e., constant clearance in the annulus. Strength properties were developed, but the performance was not equal to that produced by the Valley beater (29).

The roll refiner shown in Figure 3 was developed by Hartman (30), (31) as a means to produce internal fibrillation in the fiber structure. In addition, he also sought to determine the added influence of fines and external fibrillation. The roll refiner was quite successful at producing internal fibrillation as evidenced by transmission electron photomicrographs of treated fibers. Roll refined pulp showed no drop in freeness, although there was an increase in the water retention value (WRV). When compared with valley beating, at constant apparent density the roll refining of fibers resulted in handsheets with lower tensile strength. A 16% fines addition at two levels of roll refining resulted in a strength improvement almost equal to that produced by the valley beater.

External fibrillation was produced in an abrasion refiner developed by Higgins as cited in (30), a schematic diagram of which is shown in Figure 4. Hartman (30) found that roll refining followed by abrasion refining resulted in only an increase in density without a concomitant increase in strength. It is possible that drying effects and pulp type (sulfite) were responsible for the lack of strength improvement.

An interesting finding in Hartman's thesis (31) was a comparison of the energy consumption of roll refining and disk refining as shown in Figure 5. It is seen that roll refining reaches a strength plateau around 40 kwh/t (1.24 HPD/T), while disk refining continues to improve strength beyond roll refining, consuming around 400 kwh/t (12.4) HPD/T. It is speculated that internal fibrillation for the roll refiner is close to being more than 90% homogeneous, whereas the disk refiner, which was producing a variety of effects, e.g., internal fibrillation, fines production, etc., was much less homogeneous.

Biasca's (32) focused on internal changes in fiber structure, and he developed a bending refiner, shown in Figure 6, as a means to flex fibers. He also repeated some of the roll refining experiments of Hartman.

Biasca found that refining action in the bending refiner was in some ways different to that produced by the roll refiner. For example, out-of-plane modulus was significantly increased with the bending refiner over other methods of refining. However, the roll refiner gave a better performance than the bending refiner with respect to in-plane elastic properties.

What methods produce changes in the external structure of the fiber, i.e., external fibrillation? We have already mentioned the abrasion refiner developed by Higgins as cited in (30). Interestingly, if both surfaces of the apparatus shown in Figure 4 are smooth, no significant refining action takes place, i.e., the shear stresses are not effectively transmitted to the fiber suspension. Grit size was found to play an important role. However, the pulps were dried prior to refining for the purpose of consistency control because only small amounts of fiber were processed, and therefore, the extent to which the findings can be generalized is limited.

Cumpston (33) used abrasive grit to generate gelatinized fiber surfaces by fiber-particle interaction. The use of abrasive surfaces and abrasive particles has also appeared in the patent literature. Presumably fiber-fiber interaction will also result in external fibrillation. It is likely that methods to promote external fibrillation will also result in fines generation. The relative importance of external fibrillation in the refining of chemical pulps has not yet been established in the opinion of this reviewer.

Secondary fines generated by refining, i.e., material passing through a 200-mesh screen, can be generated by a variety of methods. At one extreme is the production of microfibrillated cellulose from softwood fibers using a homogenizer (28), as shown in Figure 7. There has recently been a flurry of activity in understanding the behavior of fines, particularly in the area of recycling (34)-(36).

As demonstrated by Hartman (30) and other researchers (34)-(36), fines can have a significant impact on many paper properties. The downside is that drainage and water removal are adversely affected. Drying generally has a negative impact on fines contribution to a number of paper properties (35).

Disk refining is currently central to real-world papermaking as mentioned earlier. It is therefore not surprising that considerable effort has been expended to better understand this process, which has been the subject of earlier reviews. More recently Martinez (7) and Kerekes and his co-workers have further contributed to our understanding of this process (7)(19)-(22). One focus of their research is to predict and measure the stresses involved in refining. How these stresses alter the structure of the fiber, and the extent to which they can be controlled, have yet to be determined. Nevertheless, their results to date are quite impressive and represent a step forward in refining research.

Silvy and his colleagues in ongoing research are viewing the refiner as a viscometer (37)-(39) in a manner reminiscent of the earlier work of Steenberg (40) and Waterhouse (29). A schematic diagram of their refiner-viscometer is shown in Figure 8. Their findings indicate that pulp behaves as a shear thinning fluid, i.e., that as refining progresses the effective viscosity decreases as the shear rate increases and fiber length decreases. The optimum properties are produced at constant load and with minimum energy consumption. In the consistency range of 2.5 to 5.0%, effective viscosity is correlated with consistency, WRV, SR (Schopper- Reigler), shear rate, and geometry.

Homogeneity of Refining

One of the major differences between laboratory refining and production refining is the homogeneity of treatment. Danforth (16) has demonstrated the impact of refining inhomogeneity on drainage and paper propertes. Hietanen (6) in Appendix II of her thesis examines this problem, and as others have concluded finds that flocs can pass through the refiner and be untreated.

The Refining Characteristics of Different Pulp Types

It is well recognized that species, pulp type, and bleaching process, and the relative amounts of thick and thin walled fibers, can affect refining. Genetic modifications, changes in pulping and bleaching, and enzyme use are all likely to impact refining. The viscoelastic-plastic behavior of wood and wood fibers is considered to be particularly important in mechanical pulping and the refining of mechanical pulps in regard to fiber separation, changes in fiber structure, and energy consumption (41)-(43).

Cellulose may be viewed as a semicrystalline material consisting of crystalline (ordered) and amorphous (less ordered) regions. Hemicellulose and the disordered regions of the cellulose chain contribute to the amorphous content and are important with respect to their association with water. Lignin, when present, is another amorphous polymer component.

Page (44) has suggested that differences in the beatability and refining action of kraft and sulfite pulps are due to differences in their viscoelastic behavior. As shown in Table 1, beating time increases as one progresses from an acid sulfite to a kraft pulp, and Page attributes this to an increase in the amorphous content of the pulp.

Table1. Beating Time (Valley Beater) to 45° SR for a 50% Yield Spruce Pulp (44).

PULP TYPE	BEATING TIME MINS.
Acid Sulfite	23
Bisulfite	25
Bisulfite-carbonate	51
Kraft	85

The differences in beating time shown in Table 1 may well be attributable to differences in viscoelastic behavior. However, this may not be the fundamental reason, and therefore, this issue requires further attention if a pulp's response to refining is to be better understood.

With regard to pulp characterization, it may be useful, in addition to monitoring the characteristics mentioned above, i.e., species, etc., to measure the % crystallinity as proposed by Salmen (45). He defined it as measured by x-ray diffraction as follows:

$$\%\ crystallinity = \frac{\text{integrated intensity of crystalline peaks}}{\text{integrated intensity of both crystalline \& amorphous peaks}}$$

Papermaking Behavior - Water Removal

As stated in the objective, we are particularly concerned with the impact of refining on paper machine runnability and paper properties. Water removal is central to machine runnability and productivity, as affected by drainage, wet pressing, and drying.

Prediction of a refined pulp's drainage characteristics is potentially the most problematic because wet end chemistry, retention, forming fabrics, and table activity can make thick stock predictions seem irrelevant.

Rapid measures of drainage include Canadian Standard Freeness, Schopper-Reigler, and Williams Slowness. Many regard these measurements as being useless, in spite of the efforts to better understand them (46), (47). More fundamental measurements of drainage include filtration resistance and its resolution into specific surface area and volume when mat compressibility behavior has been determined (58).

How the various changes in fiber structure impact these various drainage measurements is imperfectly understood. We have seen at one extreme that internal changes in fiber structure can occur with no impact on CSF, while at the other extreme, fines, because of their large surface area, can dominate CSF and other drainage measurements.

Once the web structure has been established, water removal and web consolidation in the wet press are the next important papermaking steps to be considered. Both intra and inter fiber water removal occur in the press section. Laivins and Scallan (49) have proposed that fiber saturation point (determined by the solute exclusion technique) be used as a measure of water removal in the press section. Stratton found (in unpublished work) that whereas hydrodynamic specific surface area did not correlate with water removal in the wet press, hydrodynamic specific volume did.

In processes such as impulse drying, measurement of the hydrodynamic specific surface of the web after pressing is an important parameter relating to web delamination.

Impact of Refining on Paper Properties

Basic paper properties fall into three categories, namely structure, bulk, and surface properties, examples of which are given below.

* **STRUCTURE** - Apparent density, R.B.A., and formation.
* **BULK** - Elastic properties, strength, permeability, and optical properties.
* **SURFACE** - Roughness, strength, pore structure.

A number of models have been established for predicting both elastic and strength properties (50)-(52); however, their relationship to changes in fiber structure produced by refining is still imperfectly understood. Nevertheless, the models do provide a good basis for understanding the effects of refining.

PATENT LITERATURE SURVEY 1976-1996

In addition to protection of intellectual property rights, patent literature has a variety of functions. It is a valuable source of information not readily available in textbooks or papers and can provide some sense of activity and areas of focus in a given field. Of course not everyone reveals his creativity in patents. The majority of patents document improvements in a concept, e.g., tape recorders, golf ball retrievers, disk refiners, and yet the improvements and the claims, which are their true basis, should not be obvious to one skilled in the art. In refining, we will see that patent activity has been most productive in the field of disk refining. Just as an automobile, disk refiners are better engineered today, but without any radical change in concept, e.g., the leap from vacuum tube to transistor.

This is not an exhaustive patent search, and hopefully, we have not missed significant inventions. Our focus was on new or radical concepts in refining or refining action. In addition, we hoped to have gained a limited perspective of international activity in the field of refining.

The total number of patents found in our search over the 20-year time period was 1650, and was reduced to just more than 1000 by discarding areas, which were not of immediate interest. From a general inspection of the abstracts associated with the selected patents, further subcategories of refining activity have been defined, as shown in Table 2. Although some of the patents are concerned with mechanical pulping, we are mainly interested in the refining of chemical pulps. In a number of instances, we have not always looked at the priority (or original) patent, and for many of the foreign patents, we have only examined those included in the IPST patent abstracts.

Table 2. Categories of Patent Activity in Refining.

Refining Action
Uniformity of Refining
Plate or Tackle Design
Energy Reduction
Refiner Control
Plate Materials
Novel Concepts of Refining
Additives
Plate Clearance Control
High Consistency Refining
Abrasive Materials
Steam Flow
Inlet Flow Uniformity
Fractionation
Acoustic and Ultrasonic Wave Generation
Other

Worldwide patent activity in the above categories is shown in Figure 9. A surge of activity is noted around 1980 and again in 1988. Could another surge of activity be on the horizon after the low in 1996 or has refining activity withered? Patent activity over the time period is further broken down into the major contributors of the United States, Russia and USSR, Japan, Germany, France, and Canada, and their total contributions are shown in Figure 10. Interestingly, Russia and the USSR have been the most productive, while the United States and Canada have also been very active.

We have tried to select those patents that are most directly concerned with the refining action of chemical pulps. Patent activity according to some of the categories listed in Table 2 is shown in Figure 11. As expected, activity is mainly associated with the disk refiner. In what follows, we examine some of this activity in a little more detail.

Multiple Disk Refining

One solution to the problem of uniformity is the multiple disk concept, for which patent activity (P1)-(P5) has been ongoing for a number of years. Figure 12 shows a schematic of the multiple disk refiner. Improvements to the multiple disk concept include mechanical design, uniformity of stock flow, and engineering improvements, resulting in increased plate life, and reduced energy consumption. The more recent patent (P5) is engineered to produce wobbling in order to maintain parallelism between the plates.

Plate Design

Plate or tackle design is a critical factor in most types of refiners. It is therefore not surprising that this is a very active area in the patent literature. There are many considerations, which go into plate design, including the type of furnish to be refined, the size of refining system, and the refining action or end result required.

A selection of patents on plate design is given in P6-P16, some of which are illustrated in Figure 13. Changes in refining action and fiber treatment, e.g., fibrillation, cutting, vessel element reduction, reduced energy consumption, reduced plate wear, and greater uniformity of treatment, are among the claims made, although no examples are provided in these patents to justify the claims. Findings are summarized below.

P6. Leider - spiral groove patterns
P7. Jorris - curvilinear patterns -> fibrillation and cutting
P8. Olson - abrasive disk for reduction of vessel elements
P9. Webster - spirals yielding a sliding and pinching action on fibers
P10. Demler - shortening of long fibers without treating short fibers
P11. Nilsson - successive compression and expansion to increase fiber flexibility less cutting
P12. Virving - bar angle change - better use of bar, better treatment, less energy
P13. Virving - improved dam design - to reduce plate wear
P14. Chaney - curved or zig-zag bars - ext. fib., more uniform treatment, less energy
P15. Dodd - bar design for wear reduction
P16. Wasikowski - roughness in grooves - more stable flows

A detailed study of plate design using mathematical concepts (bijective diagrams) has been made by Jorris (53).

Chemical Additives

Sometimes chemical additions are made before refining, but may have no intended effect on the action of the refiner or its efficiency, i.e., it may be a convenient point to add and obtain good mixing. On the other hand, some chemicals are purposely added to change refining action and or to reduce energy. Patents (P17)-(P21) are a few examples in the latter category, and include the use of colloidal silica to reduce refining time or energy and sodium hydroxide for the same purpose. In high-yield pulps, sulfonated chitosan is suggested as an additive to reduce energy and improve paper strength.

Disk and Conical Refiners

In this category, we consider a few patents that deal with solutions to problems arising in disk refining, including flow control, flow uniformity, fiber clogging, deflocculating stock, screening and refining untreated stock, and energy savings.

The Reinhall patent (P22) describes the prior art concerned with radial stock flow, due to centrifugal forces and steam flow, and its retention in the refining zone of the plates using a stator ring at the periphery of the disk as shown in Figure 14. Grinding (or refining) also takes place in the outer zone.

Uniformity of flow through the refining zone in a disk-type refiner is achieved by using one conventional plate in conjunction with a perforated plate (P23) as shown in Figure 15. The objective being to treat a greater proportion of the stock.

Cumpston's patent (P24) deals with the problem of controlling radial flow in the attrition zone of a disk refiner and the problem of fiber clogging.

A fluidizing inlet to a disk refiner (see Figure 16) as a means to deflocculate the stock entering the refining zone is the essence of the patent by Brown (P25). The principle involved is basically the same as that proposed by Hietanen and Ebling (5). Brown's patent claims that stock consistency can be increased, thereby reducing refining energy.

The intention of patent (P26) is not altogether clear. The abstract claims that if fibers are fed between two flat circular disks with the right pressure differential long fiber pulp fibers can be produced.

A difference in disk speed in a double disk refiner is used to accomplish in a low speed refiner (1200 rpm) what is accomplished in a high speed refiner (1800 rpm), i.e., savings in energy and the same reduction in CSF, details of which are given in patent (P28).

Novel Refiners

By novel refiners, we mean refiners other than disk or conical, which may potentially be used in a laboratory or mill production situation. Patent activity in this area has been relatively light, with the possible exception of the USSR-Russia. Some examples have been selected, (P29)-(P35).

Disk and conical refiners have evolved as refiners of choice. Nevertheless, it still remains a challenge to produce a refiner, which has better control of refining action and the effects of refining, more uniform in its treatment with less energy consumption.

In the absence of chemical effects, e.g., creation of osmotic stresses, one of the prime requirements is the effective transmittal of mechanical stresses to the fibers.

McMillan's device (P29) is a novel approach to mechanical pulping, which involves an unravelling of the fiber structure by subjecting it to torsional stresses. The concept of multiple contact using abrasive particles is a challenging general problem in areas such as size reduction, grinding, attrition, and milling. The success of patents (P30) and (P34) in addressing this problem is not known.

Clark (54) has made many contributions to refining and pulp characterization. He was particularly enthusiastic about the Kollergang (54) and sought to embody its principles in the Kollermill (P33), an intended production-scale refining device. Clark's device (P33) and Shemyakin and Sitov's device (P32) are, in some ways, similar to Hartman's device (30) discussed earlier, although there is no lateral oscillation in their devices.

THE FUTURE OF REFINING

One can envisage two extremes. One scenario is a radical new concept of refining, and the other, the development of fibrous materials such that little or no refining is required. The latter situation may be brought about by genetic engineering, enzyme and chemical treatments, and improved methods for the fractionation and blending of raw materials. The latter option may simplify the papermaking process and even save energy. Efforts to improve refining will probably continue from both ends of the spectrum in order to satisfy current and future papermaking needs.

ACKNOWLEDGEMENTS

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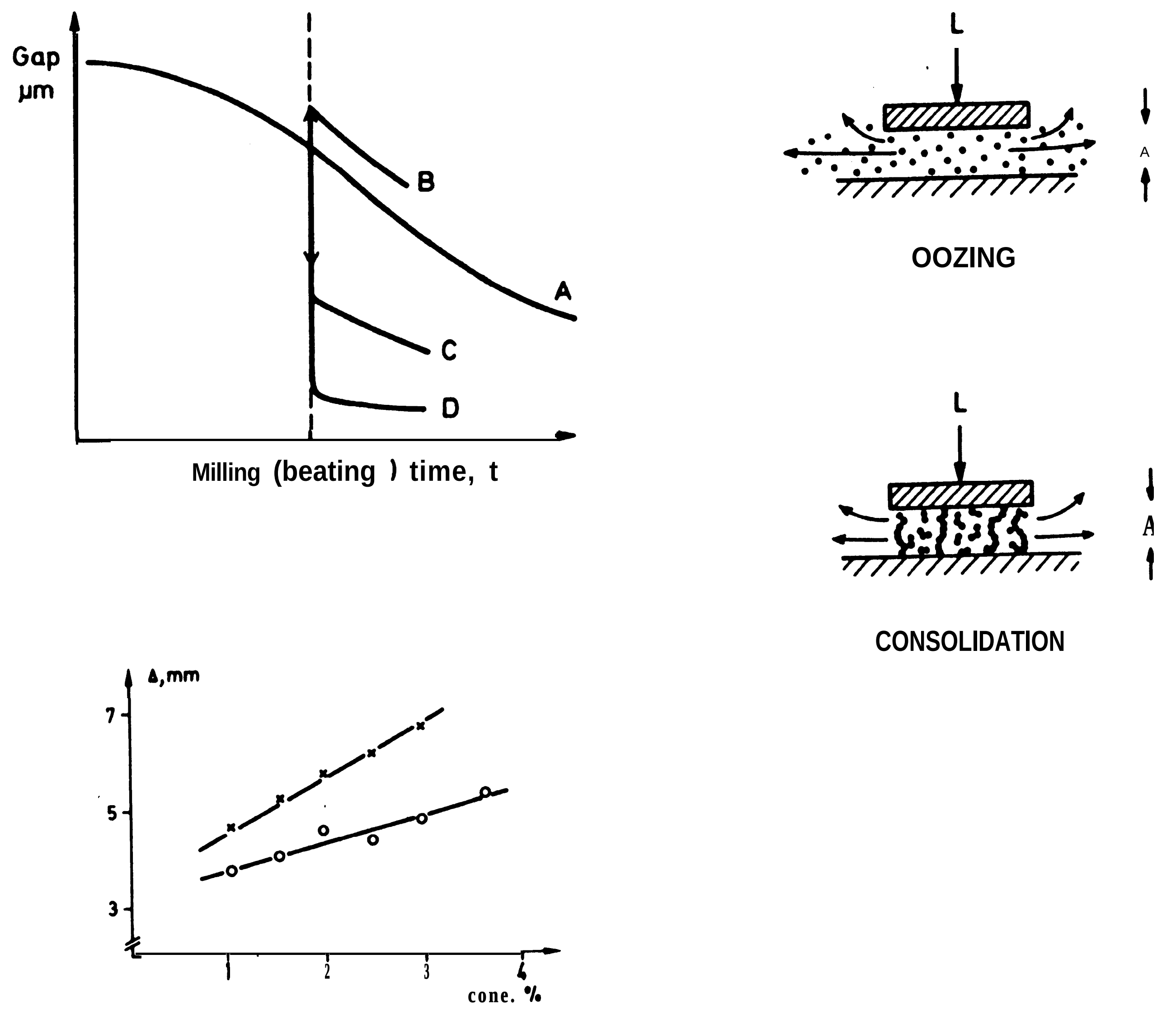


Figure 1. Steenberg's Refining Concepts Taken from (23)-(25).

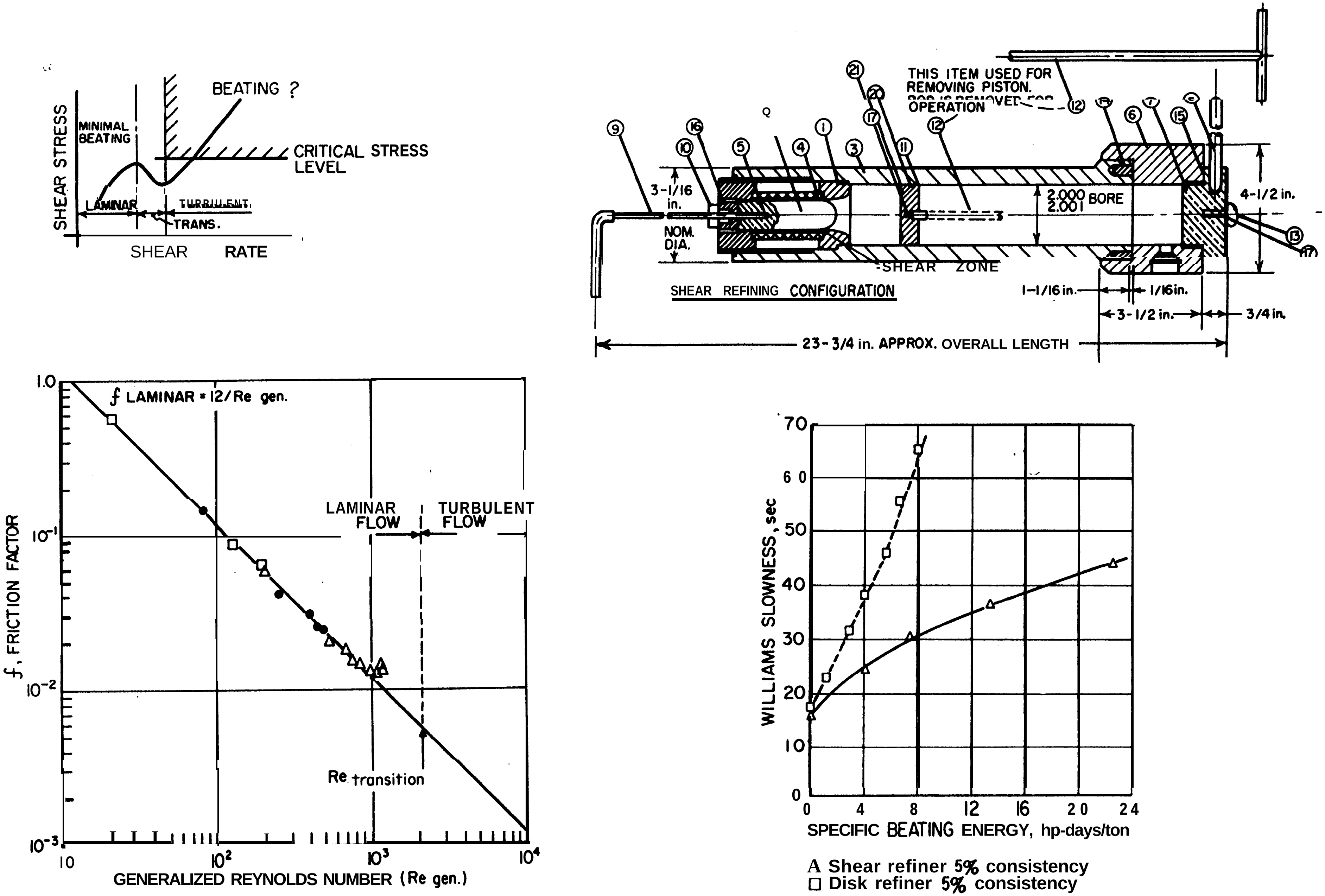


Figure 2. "Shear Refiner" Taken from Waterhouse (29).

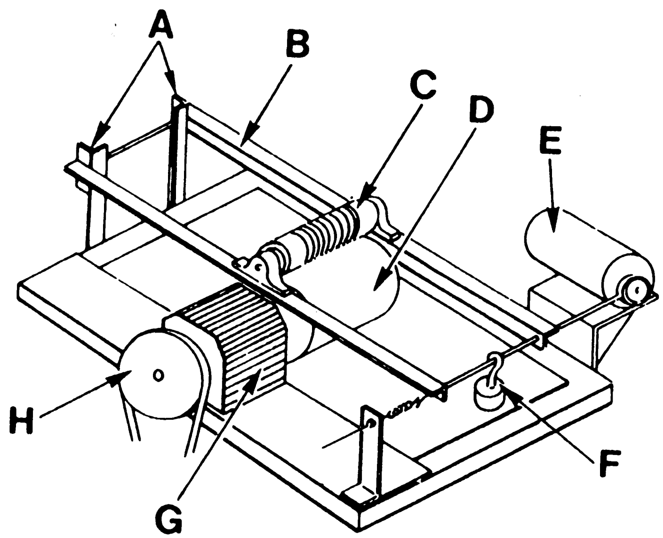


Fig 1—Schematic of roll refiner

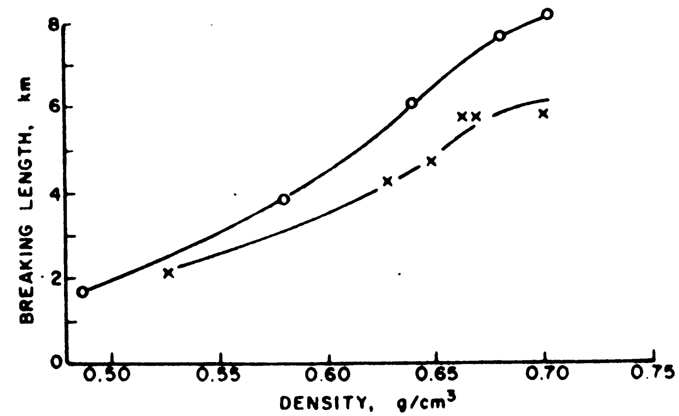
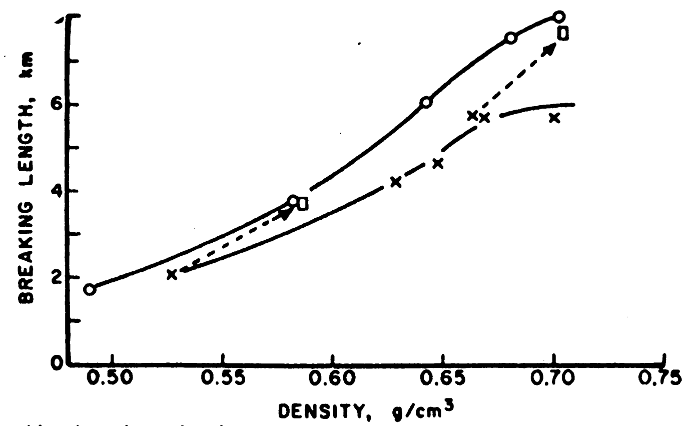


Fig 3—Breaking length vs density
x = roll refined, o = Valley beaten



—Breaking length vs density
x = roll refined, o = Valley beaten, □ = fines addition

Figure 3. "Roll Refiner" Taken from Hartman (30).

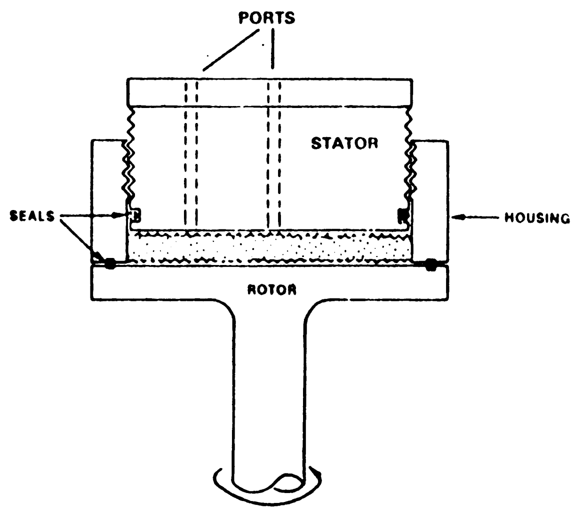


Fig 2—Schematic of abrasion refiner

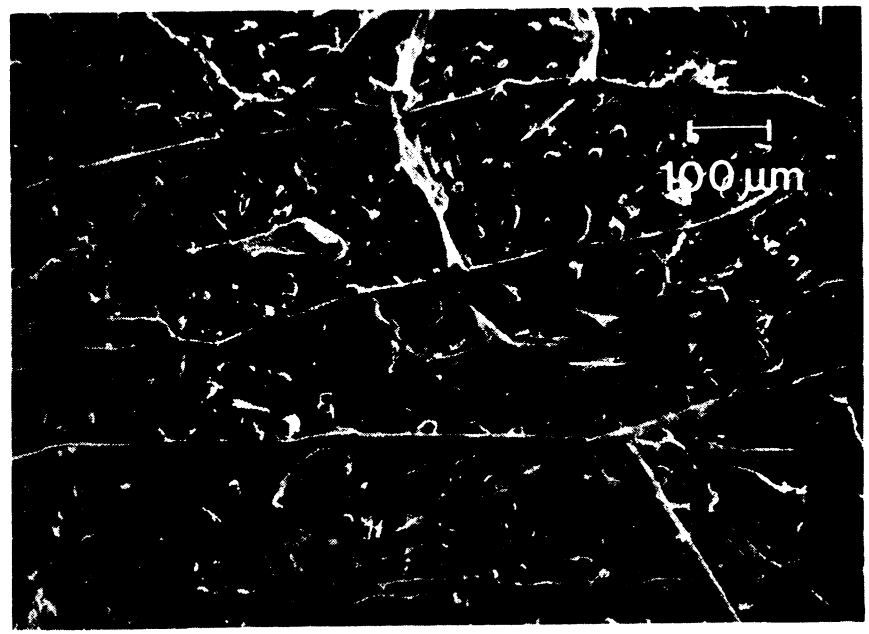


Figure 4. "Abrasion Refiner" Taken from Hartman (30).

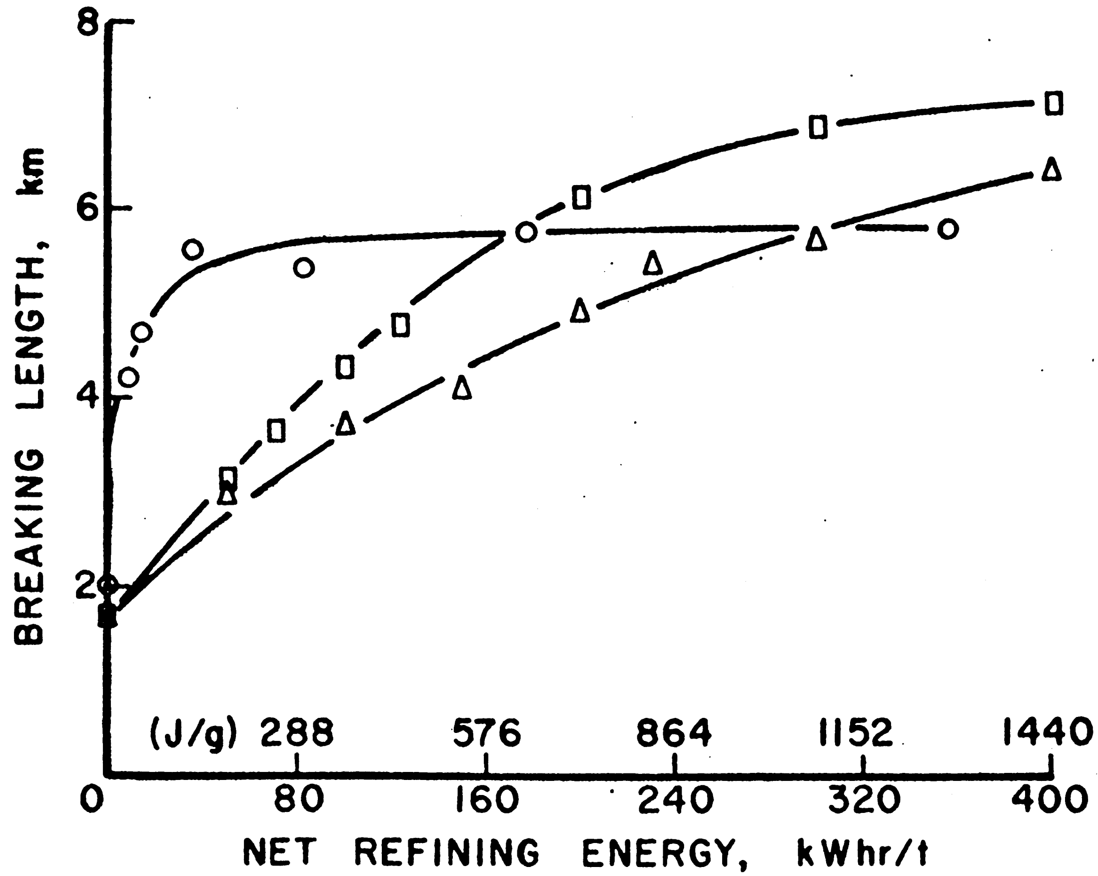


Figure 5. Refining Energy - Roll Versus Disk Refiner Taken from Hartman (31).

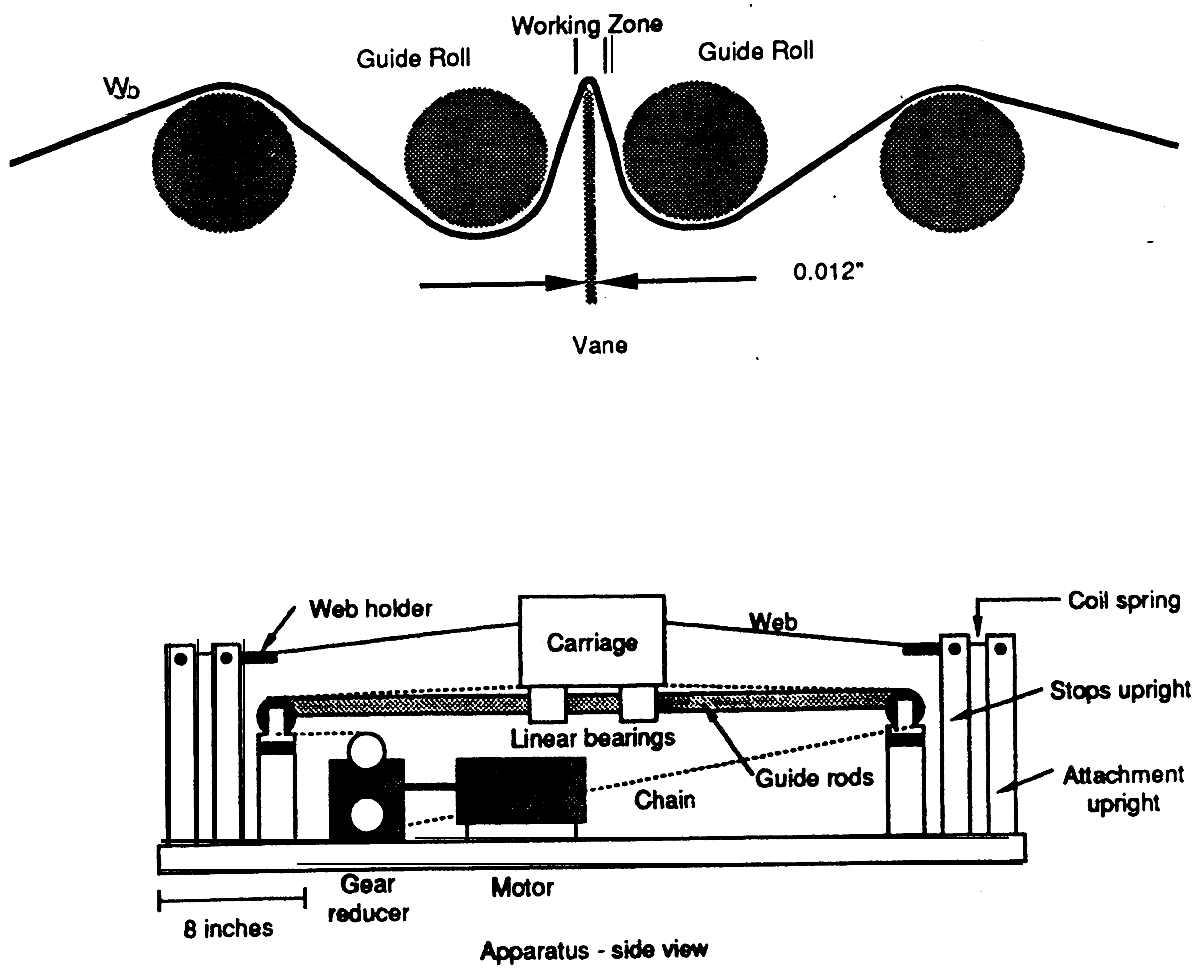


Figure 6. "Bending Refiner" Taken from Biasca (32)

* **APV GAULIN HOMOGENIZER**

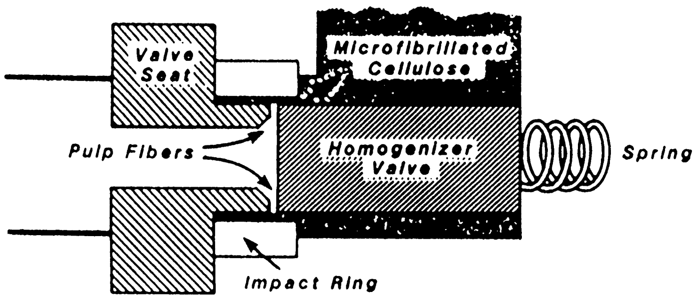


FIG. 1. Schematic representation of homogenizer action.

FIGURE 2 SEM OF STARTING PULP C (1000X)

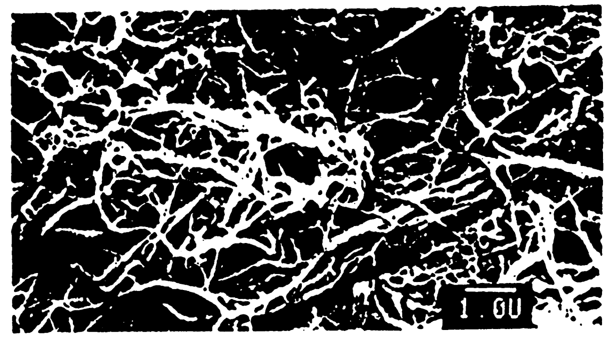


FIGURE 3
SEM OF MICROFIBRILLATED PULP C (10000X)

* **SPECIFIC ENERGY = 1.0707 X 10^{-4} P/C HPD/TON**

where P is stagnation pressure (8,000 psi max.) and C is consistency or solids fraction.

Example: P=8,000 psi, C=5%; Specific Energy = 17 HPD/T

Figure 7. "Homogenizer" Taken from (28).

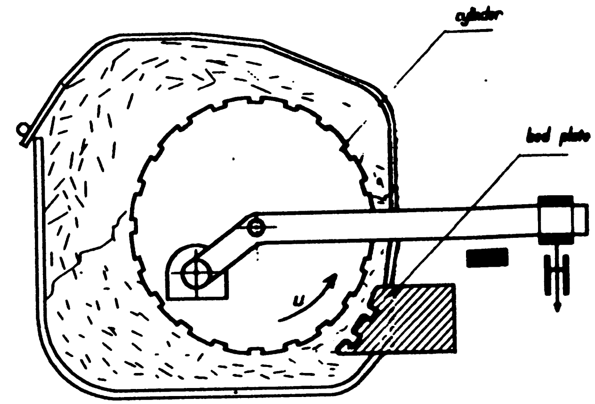


Figure 8. "Refiner-Viscometer" Taken from (41).

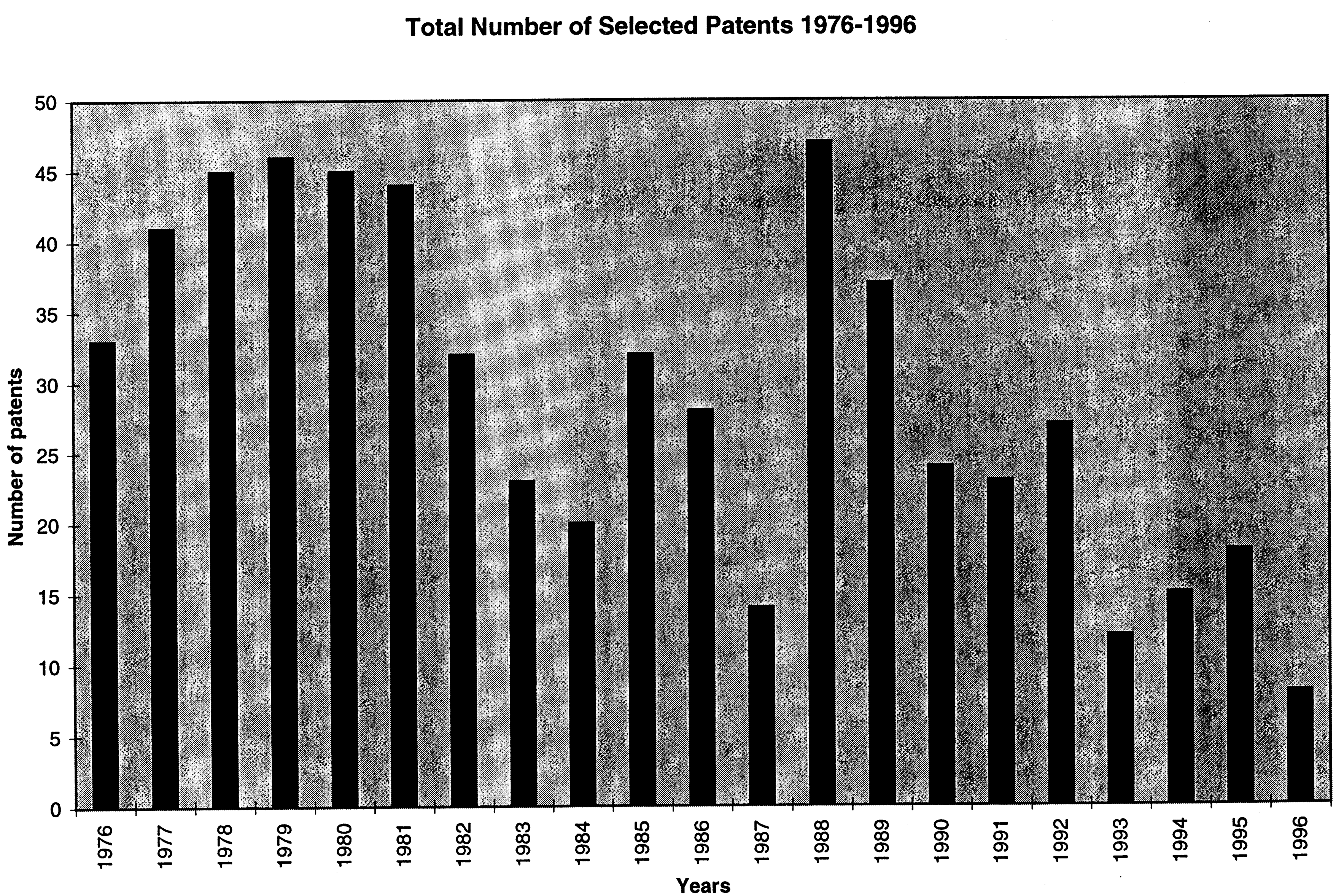


Figure 9. Selected Patent Activity Worldwide Between 1976-1996.

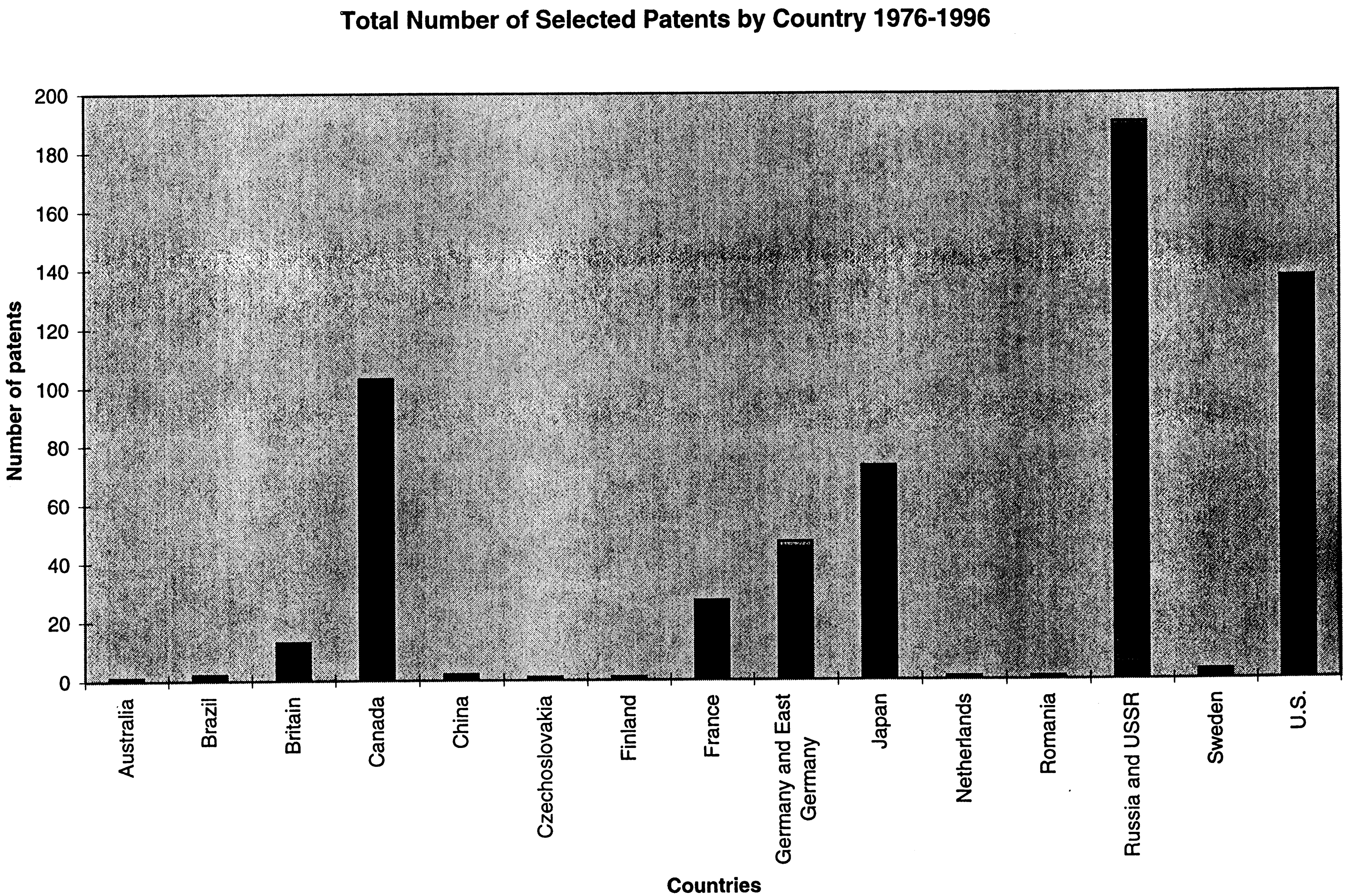


Figure 10. Total of Selected Patents by Country Between 1976-1996.

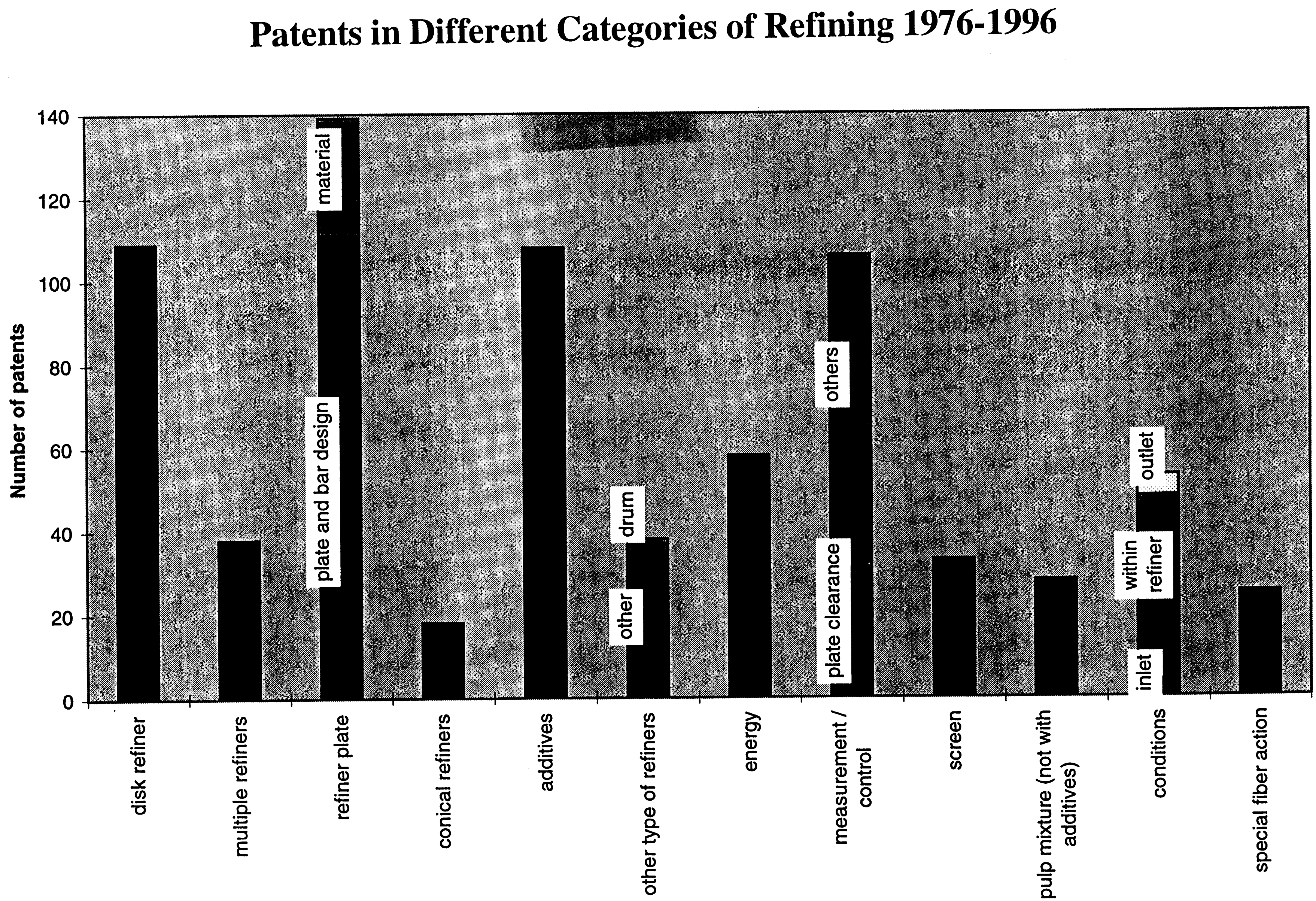


Figure 11. Patent Activity in Different Categories of Refining 1976-1996.

FIG. 2

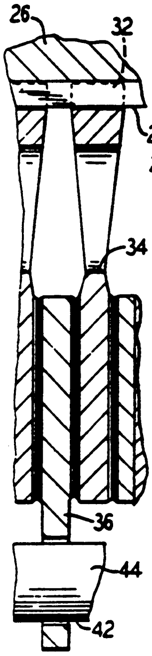


FIG. 1

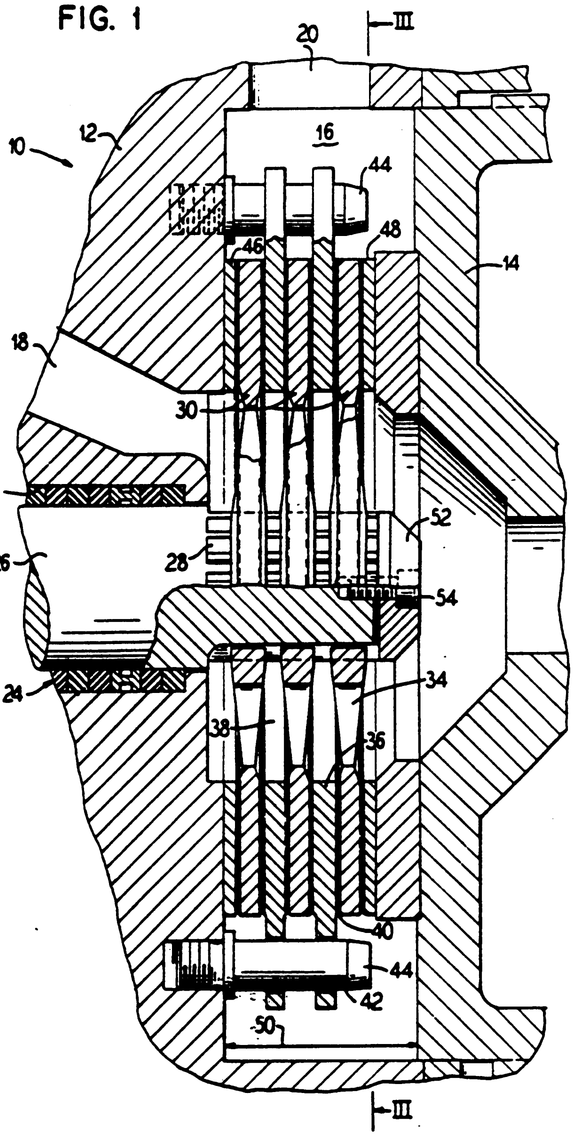
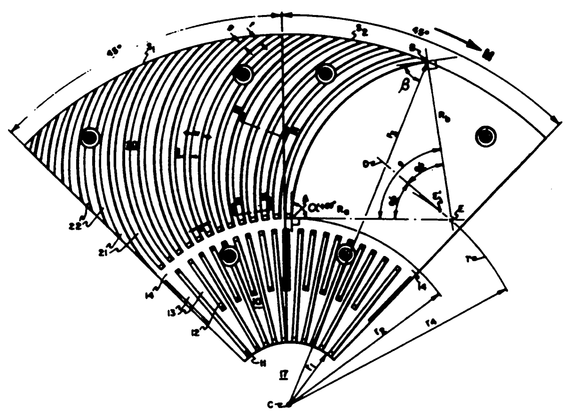
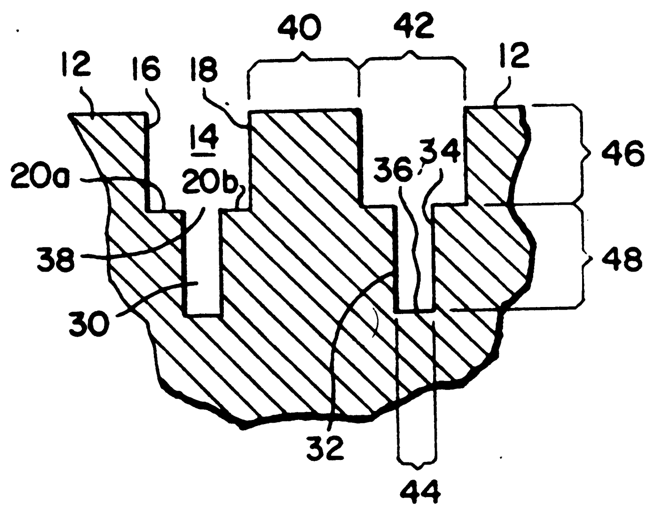


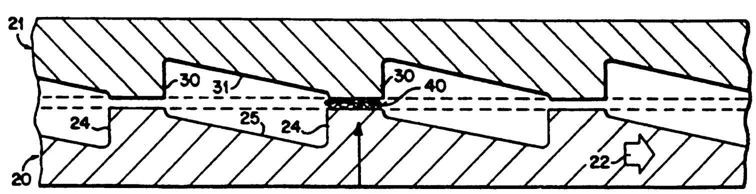
Figure 12 Multiple Disk Refiner taken from Fredriksson, B. and Goldenberg, P.H. (P4)



Taken from Leider, P.J. and Rihs, J (P6)

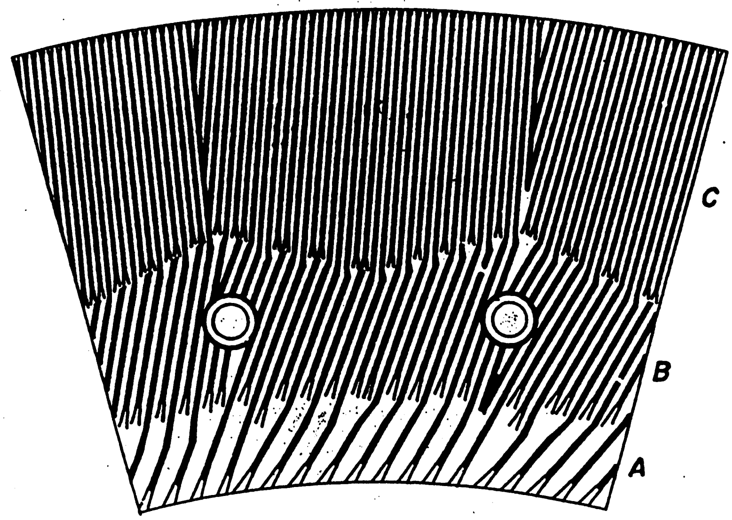


Taken from Demler, C.L. (P10)

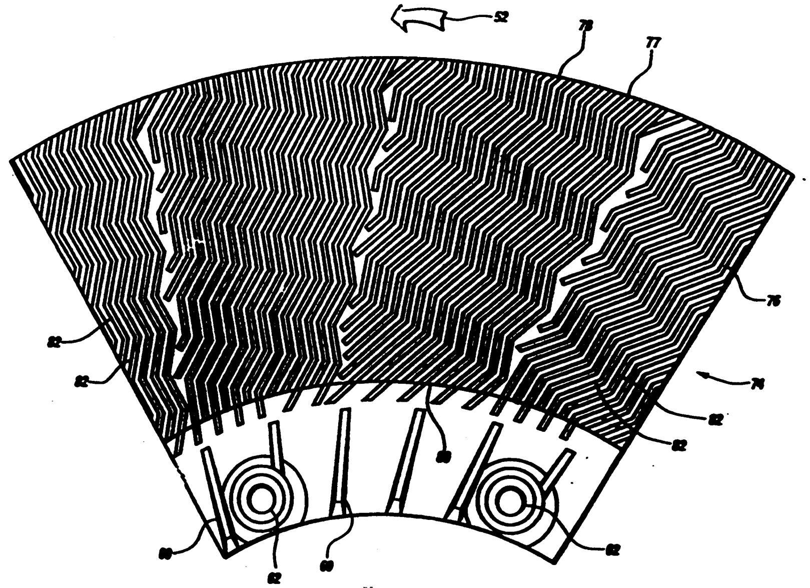


Taken from Nilsson, B. (P11).

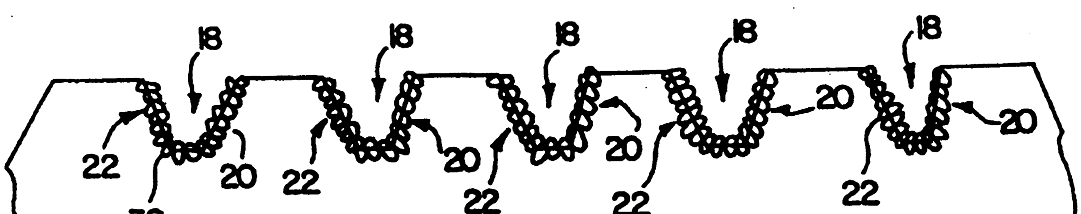
Figure 13 Selection of Plate Designs



Taken from Virving,N. (P12).



Taken from Chaney, M.R. (P14).



Taken from Wasikowski, P. (P16).

Figure 13 Selection of Plate Designs (contd.)

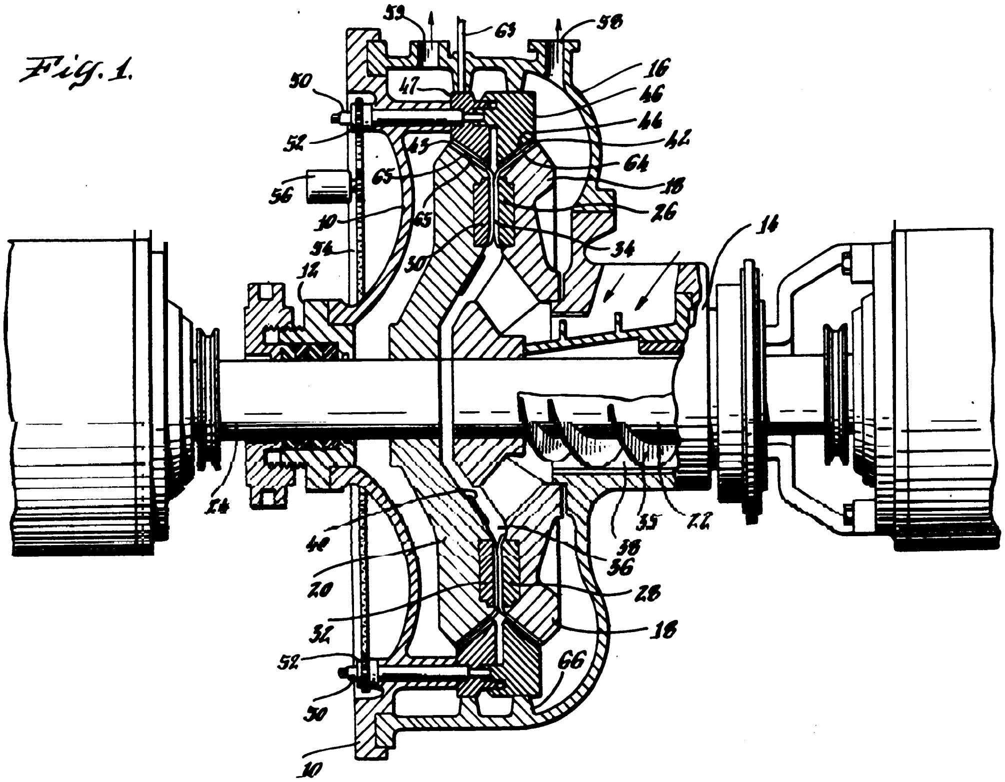


Figure 14 Apparatus of Reinhall, R.B. Taken from (P22).

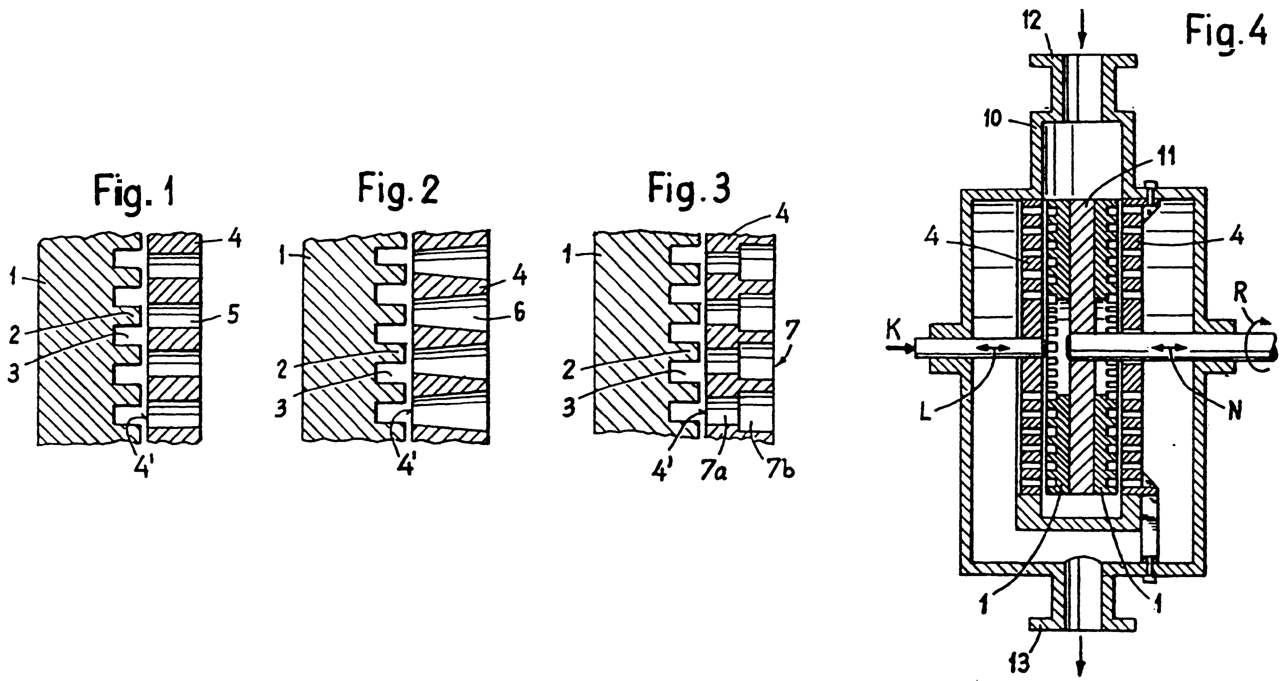


Figure 15 Apparatus of Sepke, P.W. Taken from (P23).

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FIG. I

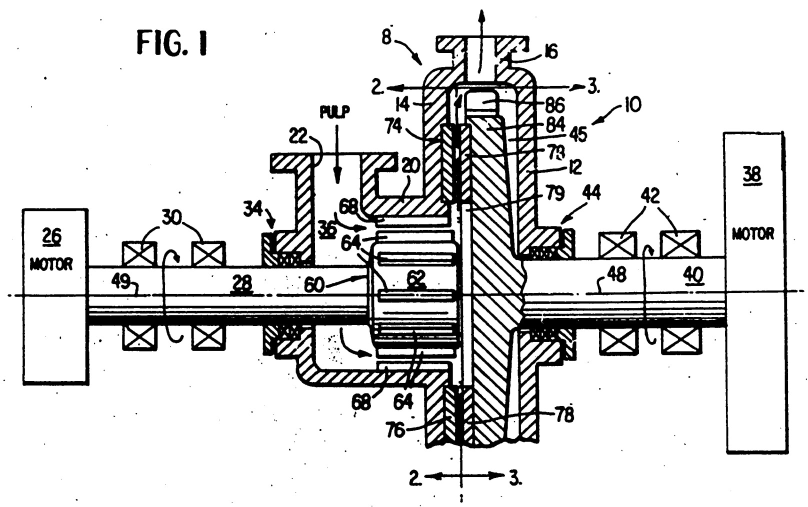

Figure 16 Apparatus of Brown, K.J. Taken from (P25).